REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
13 October 2015

2. REPORT TYPE
Briefing Charts

3. DATES COVERED *(From - To)*
21 September 2015 – 13 October 2015

4. TITLE AND SUBTITLE
Laser Diagnostics for Spacecraft Propulsion

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Natalia A. MacDonald-Tenenbaum

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
Q18B

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQRS
1 Ara Drive
Edwards AFB, CA 93524-7013

8. PERFORMING ORGANIZATION REPORT NO.

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RQR
5 Pollux Drive
Edwards AFB, CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RQ-ED-VG-2015-372

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
For presentation at Gaseous Electronics Conference 2015; Honolulu, HI; October 13, 2015
PA Case Number: # 15625; Clearance Date: 10/15/2015

14. ABSTRACT
Briefing Charts/Viewgraphs

15. SUBJECT TERMS
N/A

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			N. MacDonald
Unclassified	**Unclassified**	**Unclassified**	SAR	19	**19b. TELEPHONE NO** *(include area code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Air Force Research Laboratory

68th Annual Gaseous Electronics Conference

LASER DIAGNOSTICS FOR SPACECRAFT PROPULSION

GEC15-2015-000599

Tuesday, October 13, 2015

Natalia MacDonald-Tenenbaum
In-Space Propulsion Branch
Air Force Research Laboratory
Edwards AFB, CA
natalia.macdonald@us.af.mil

Integrity ★ Service ★ Excellence

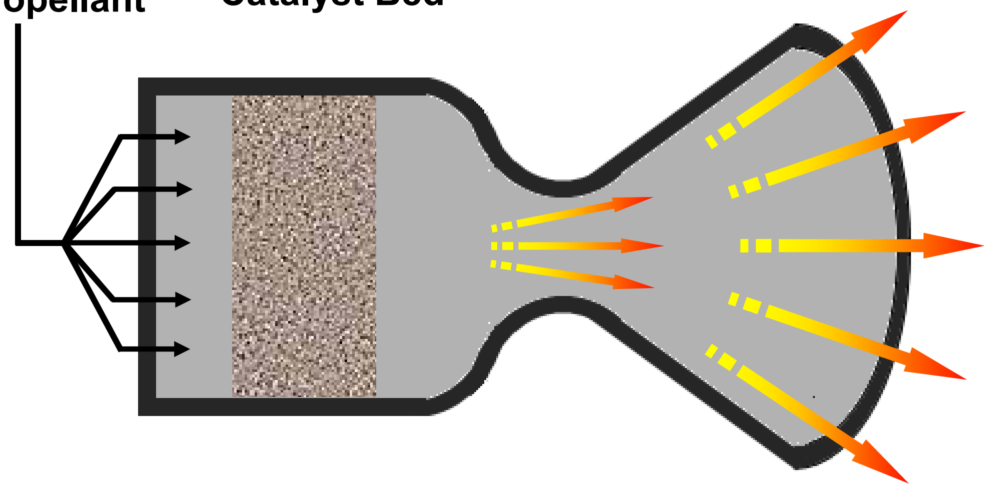
Outline

- Motivation
- Monopropellant thrusters
  - Diode Laser Absorption Spectroscopy (DLAS)
  - Wavelength Modulation Spectroscopy (WMS)
- Arcjets
- Hall thrusters/Ion engines
  - Laser Induced Fluorescence (LIF)
  - Time resolved LIF Methods
- Recent results from Time-Synchronized LIF
  - Time-Sync Method
  - BHT-600 Results
- Summary
- References

Motivation

- **Many satellite propulsion technologies were developed in the 1960s**
  - **Didn’t have the diagnostics to fully understand how/why they worked**
  - **Aging workforce causing us to lose knowledge of how the systems were made, recipes for materials, trade secrets, etc.**
  - **Now having to go back and characterize old systems to lay groundwork for advancements in technologies**
- **Tunable diode lasers developed in the 1960s**
  - **Diagnostic techniques have been developed alongside propulsion technologies**
  - **Simulation of space environment, rarefied gases – facility effects become important**
  - **Laser diagnostics non intrusive, can survive harsh environments of combustion, plasmas**
- **New methods of laser diagnostics**
  - **Provide insight into dynamics of thruster operation**
  - **Are linked to thruster performance metrics**
  - **Are critical to validating numerical simulations**

Monopropellant Thrusters



Aerojet MR-106
Propellant: Hydrazine
Thrust: 22 N   Isp: 235 sec

Operation

- Monopropellant flows over catalyst bed to initiate exothermic decomposition
- Propellant is expanded and accelerated out of a nozzle
- Developed in 60s, having to now go back and figure out how they work

Diagnostics

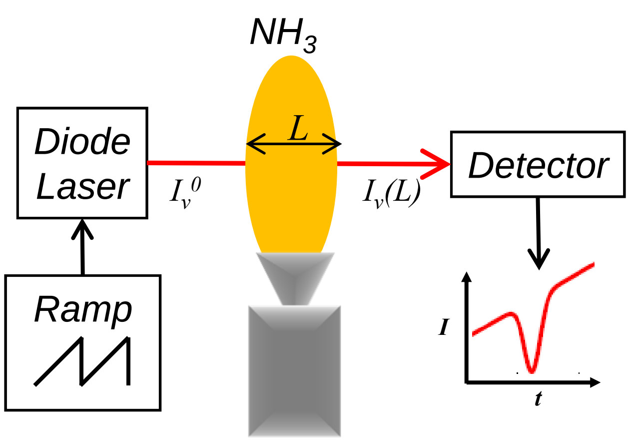
- Destructive testing the current standard
  - Intrusive, post-test
  - Cut open thruster to examine catalyst
- Diode Laser Absorption Spectroscopy
  - Non-intrusive, in-situ measurements
  - Temperature, species concentrations
  - Wavelength Modulation Spectroscopy (WMS)
- Other methods such as FTIR, PLIF, emission spectroscopy on combustion/propellants, not on thrusters in operation

Diode Laser Absorption Spectroscopy

Beer-Lambert Law

$$I_\nu(L) = I_\nu^0 \exp(-k_\nu L)$$

$I_\nu(L)$	Transmitted spectral intensity after traveling through a distance, L, through the medium [W/cm^{2}s^{-1}]
I_ν^0	Initial spectral intensity of the laser per unit frequency [W/cm^{2}s^{-1}]
k_ν	Spectral absorption coefficient [cm^{-1}]



Hydrazine Thruster

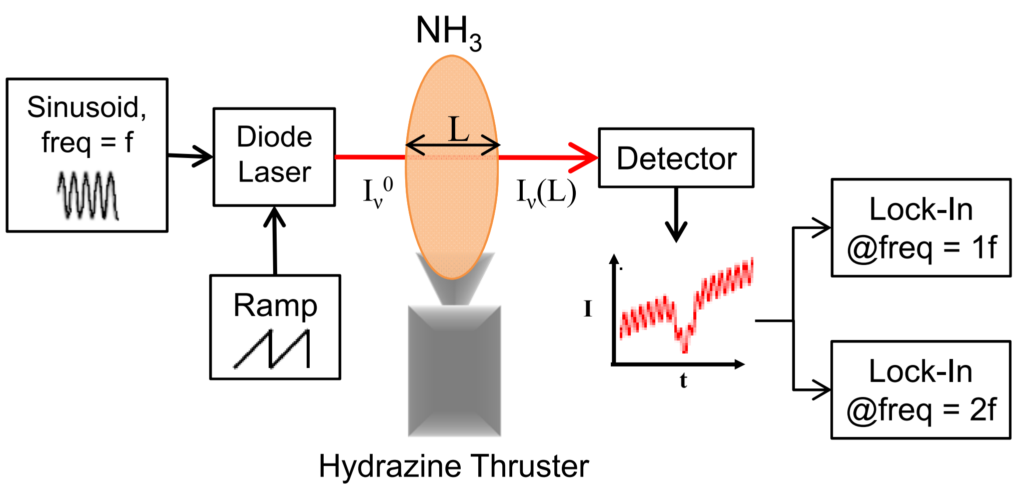
- **Ramp input to laser**
  - Modulates intensity and wavelength (modulation frequency up to 1 MHz)
  - Baseline fit + Beer-Lambert Law gives absorbance of spectral feature
- **Species Identification**
  - k_ν can be related to number densities, partial pressures to detect concentrations of combustion products such as NH_3
  - Presence of different species indicates catalyst health
- **Temperature**
  - FWHM of transition indicates temperature (if no pressure broadening)
  - Ratio of two nearby transition intensities indicates temperature (pressure independent)
  - Lowering temperature indicates degradation of catalyst

Wavelength Modulation Spectroscopy (WMS)

1f-normalized WMS-2f

- **Diode laser modulated in wavelength and intensity via:**
  - Current injection at frequency = 1f
  - Ramp voltage
- **Detector output sent through two lock-in amplifiers**
  - Reference frequencies = 1f and 2f
  - Comparison of 2f signal ("WMS-2f") to model of absorption feature indicates temperature and gas concentration

➢ **Improved sensitivity and noise-rejection over direct absorption (2 to 100x better SNR)**



- **2f signal is related to the original absorption feature by a mathematical transform**

$$I_\nu(L) = I_\nu^0 H_n(\bar{\nu}) L$$

$$H_n(\bar{\nu}) = \frac{2^{1-n}}{n!}\alpha_n \left.\frac{d^n \alpha(\nu)}{d\nu^n}\right|_{\nu=\bar{\nu}}$$

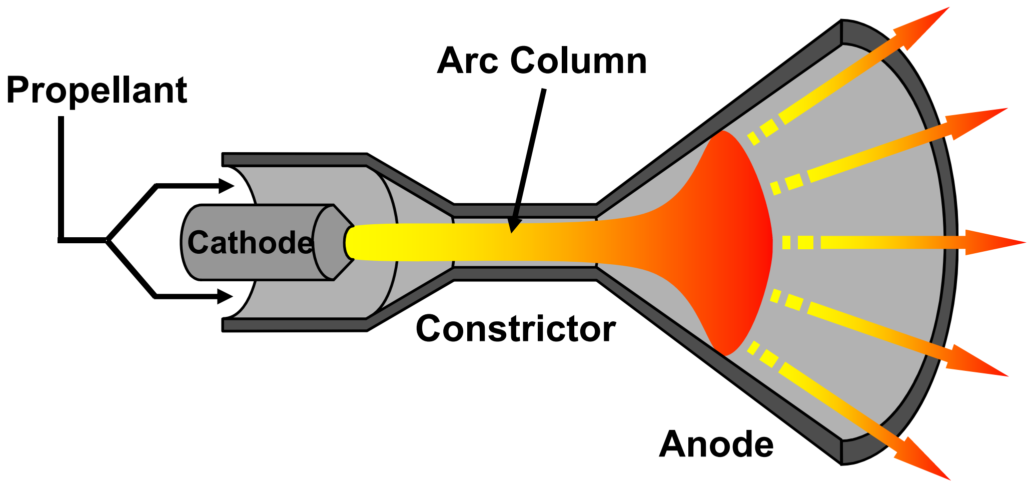
  - H_n^{ν} = nth Fourier component of modulated absorption coefficient (n=2 for WMS-2f)
  - α(v) = absorption coefficient (modeled by Gaussian, Lorentzian, Voigt)
  - v = mean modulation frequency

- **Normalization of 2f signal by 1f signal eliminates effects of laser intensity drift, scattering, etc.**

$$\frac{2f}{1f} = \frac{H_2}{i_0} = \frac{S(T)\cdot P\cdot x_i\cdot L}{i_0\cdot \pi}\int_{-\pi}^{\pi}\phi\left(\bar{\nu}_{peak} + a\cos\theta\right)\cos 2\theta\, d\theta$$

  - **S(T) = Linestrength at temperature = T**
  - **x_i = species concentration**
  - **i_0 = incident laser intensity**
  - **φ = linseshape function (Gaussian, Lorentzian, Voigt)**
  - **a = amplitude of frequency modulation**

Arcjets



Aerojet MR-510 Arcjet
Propellant: Hydrazine
Thrust: 250 mN   Isp: 585 sec

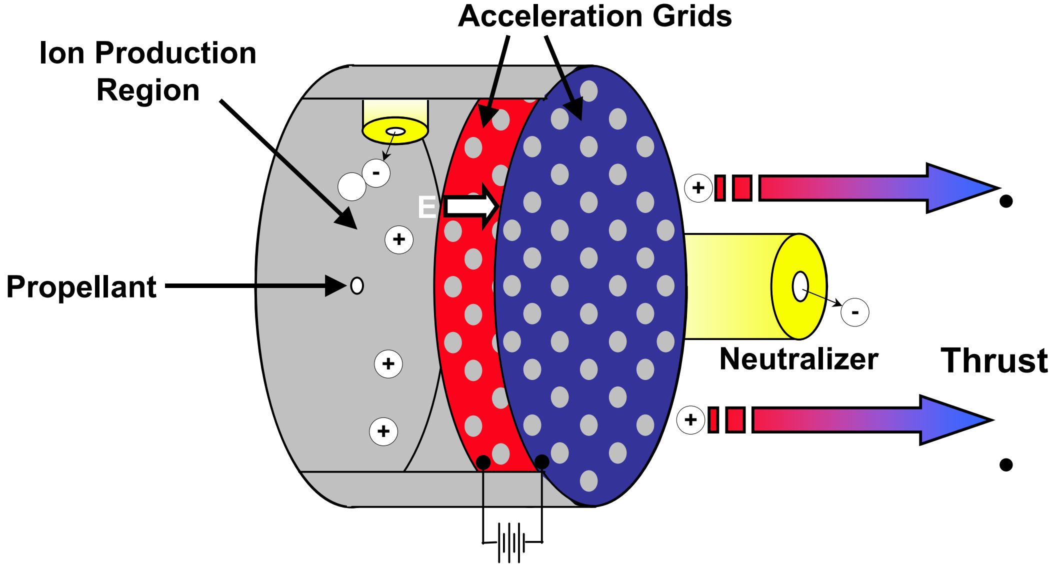
Operation

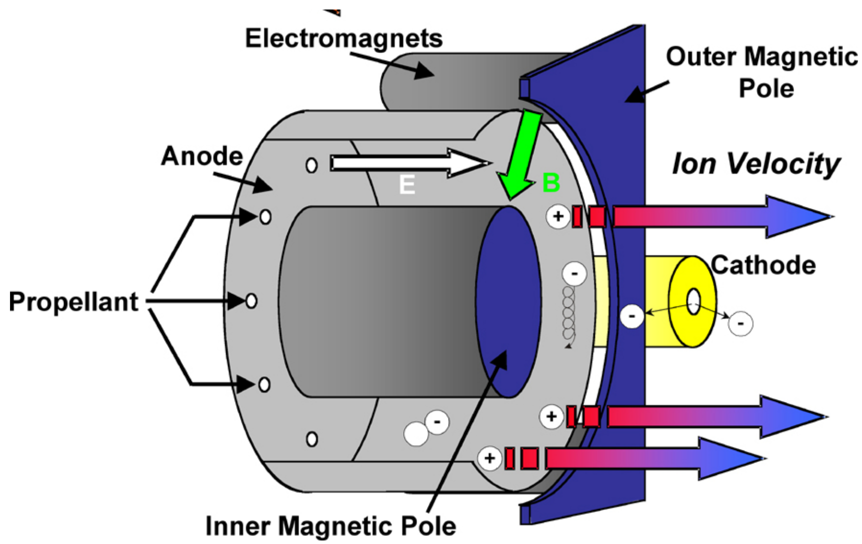
- Electrothermal thruster
- Heats a gaseous propellant (hydrazine, NH_3, H_2)via electrical arc
- Propellant is expanded and accelerated out of a nozzle similar to chemical thrusters

Diagnostics

- Laser Induced Fluorescence
  - Velocity, temperature measurements
  - Development of LIF techniques
    - Hydrogen plasma
- Raman spectroscopy

Ion Engines & Hall Thrusters





Operation

Ion engines and Hall thrusters are electrostatic propulsion devices

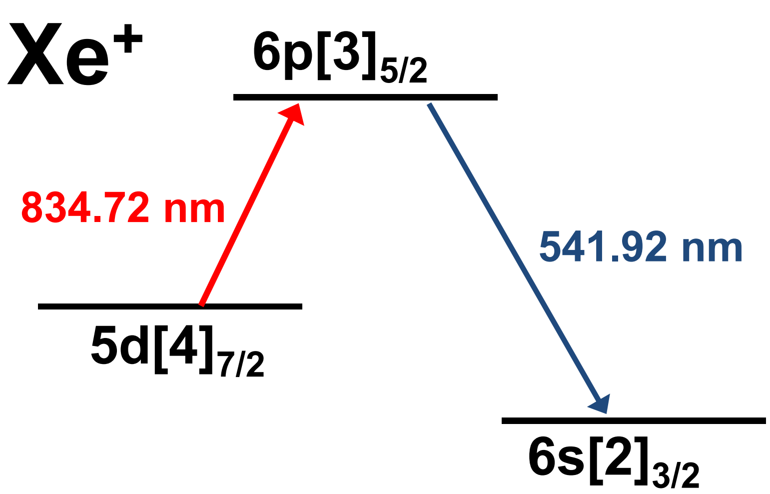
- Ion Engines
  - Propellant is ionized via electron bombardment and then accelerated by high voltage grids
  - Thrust, Isp, Propellant: Xenon
- Hall thrusters
  - Hall thrusters are gridless electrostatic thrusters
  - Propellant ionized by electrons trapped in magnetic field
  - Ions accelerated by an electric field between anode and electron cloud
  - Thrust, Isp, Propellant: Xenon, Krypton

Diagnostics

- Laser Induced Fluorescence
  - Velocity, temperature measurements
- Diode Laser Absorption Spectroscopy
  - Metastable neutrals

Laser Induced Fluorescence

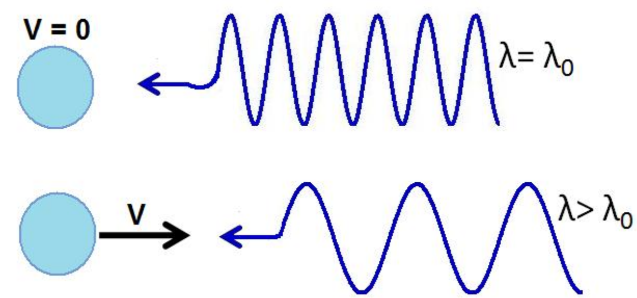
- **Laser beam tuned across electronic transition in Xe ions**
  - *$5d[4]_{7/2}$–$6p[3]_{5/2}$ at 834.72 nm*
- **Ions spontaneously emit photons resulting in their relaxation from its excited state to a lower state (fluorescence)**
  - *$6s[2]_{3/2}$ –$6p[3]_{5/2}$ at 541.92 nm*

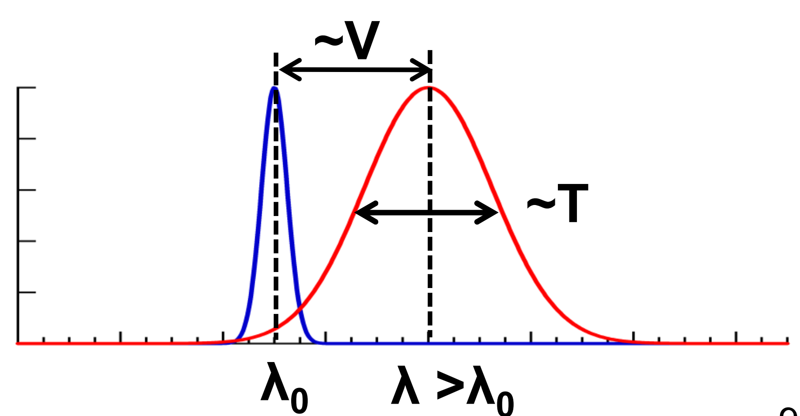


Non-resonant fluorescence scheme

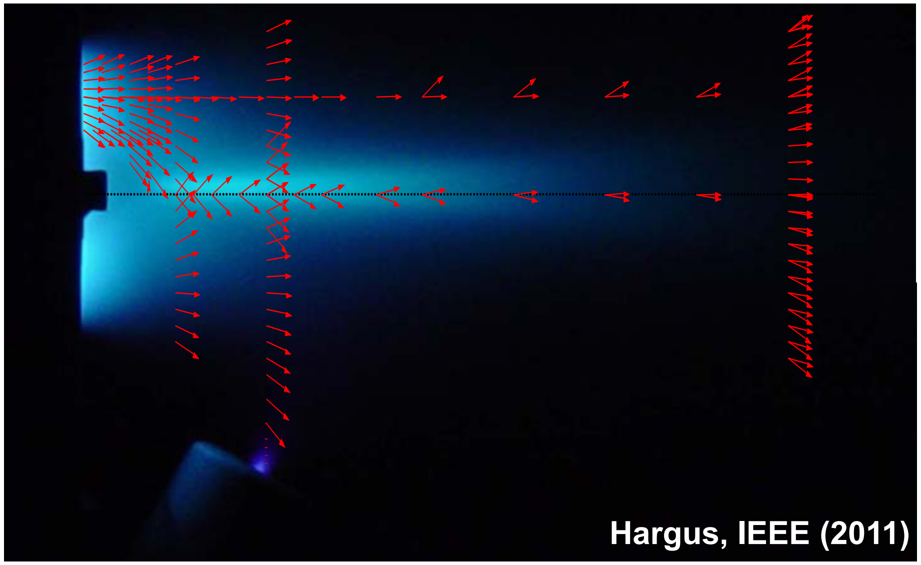
- **Fluorescence excitation spectrum**
  - **Convolution of ion velocity distribution function (VDF), transition lineshape (inc. hfs, etc.)**
  - **Shape (broadening/shift) dominated by Doppler effect:**

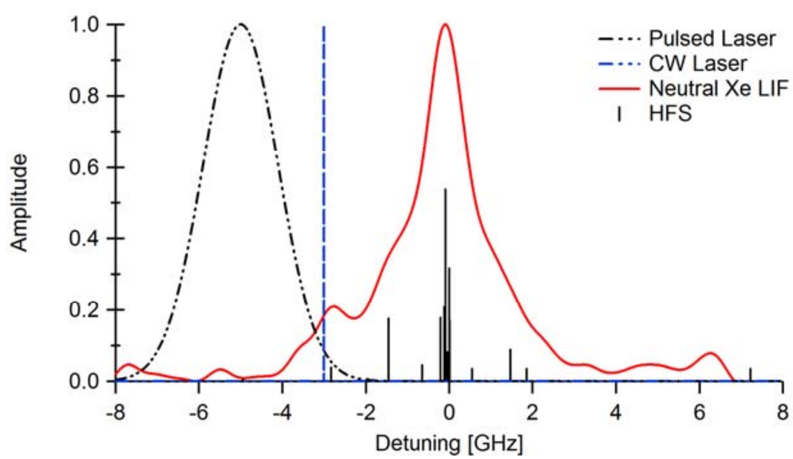
$$\delta\nu_{12} = \frac{V}{c}\nu_{12}$$





Laser Induced Fluorescence Velocimetry





Lineshape of the 834.68 nm Xe transition compared to widths of a pulsed laser and a CW laser. Hyperfine structure (HFS) shown as reference.

- **Measurement of time-averaged velocity vectors**
  - **Non-intrusive measurements in channel and near field plume**
  - **High spatial resolution (~1mm)**
  - **High spectral resolution can resolve multiple velocity populations**
  - **Temporal resolution eliminated by need for long integration times (>100 ms)**
- **Necessary to develop time-resolved LIF velocity measurements**
  - **Resolve oscillatory behavior of thrusters**
  - **Inform M&S for S/C interactions**
- **CW diode lasers required to take time resolved LIF measurements**
  - **Typical linewidth of pulsed laser is larger than desired**
  - **CW Diode Laser: < 300 kHz**
  - **Pulsed Nd:Yag Dye Laser: > 1.5 GHz**
  - **Doppler width of transition: < 2 GHz**

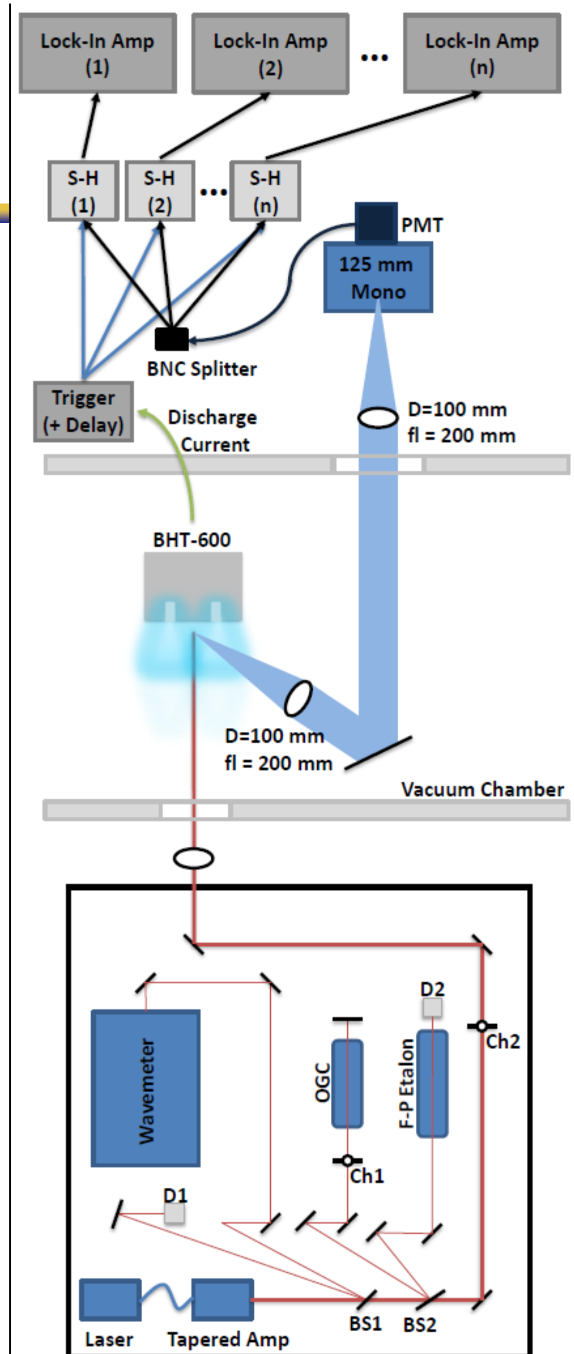
Experimental Apparatus

- **New Focus Vortex TLB-6917 tunable diode laser used to seed a TA-7600 VAMP tapered amplifier**
  - 60 mW output power
  - Xenon ion (Xe II) transition at 834.72 nm probed ($5d[4]_{7/2}$–$6p[3]_{5/2}$)
  - Non-resonant fluorescence collected at 541.92 nm ($6s[2]_{3/2}$ –$6p[3]_{5/2}$)

- **Stationary xenon neutral (Xe I) reference**
  - 9.03 GHz distant $6p'[3/2]_1$–$8s'[3/2]_1$

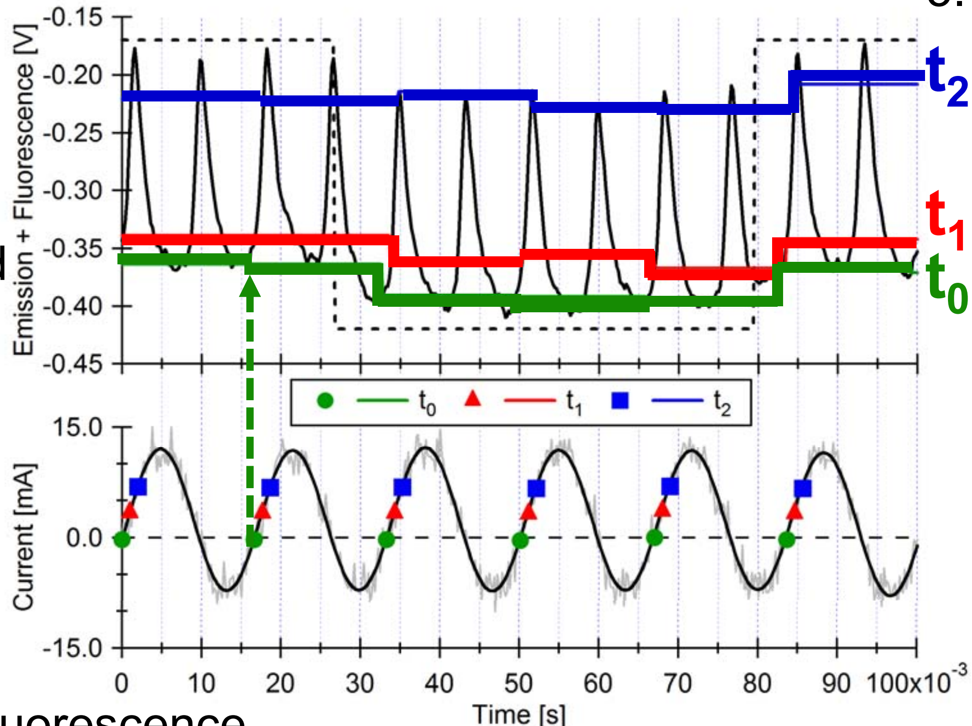
- **Parallelized sample-hold method of time-synchronization**
  - 6 time points taken simultaneously

➢ **9x improvement in data acquisition efficiency**
  ➢ Better signal-to-noise
  ➢ Faster data acquisition



Time-Synchronized Laser Induced Fluorescence

1. Take simultaneous measurements of AC discharge current, emission + fluorescence
2. AC current from the discharge is fed into a comparator to find zero point crossings (reference point for time = t_0)



3. Raw emission + fluorescence trace and comparator signal sent into sample-hold circuit (samples at t_0 trigger, holds value)
4. Sample-hold repeats at t_0 points along entire scan
5. Pass sample-held signal through lock-in amplifier

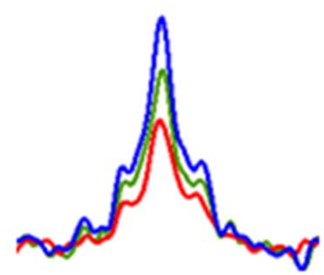
↓

Fluorescence excitation lineshape for t_0

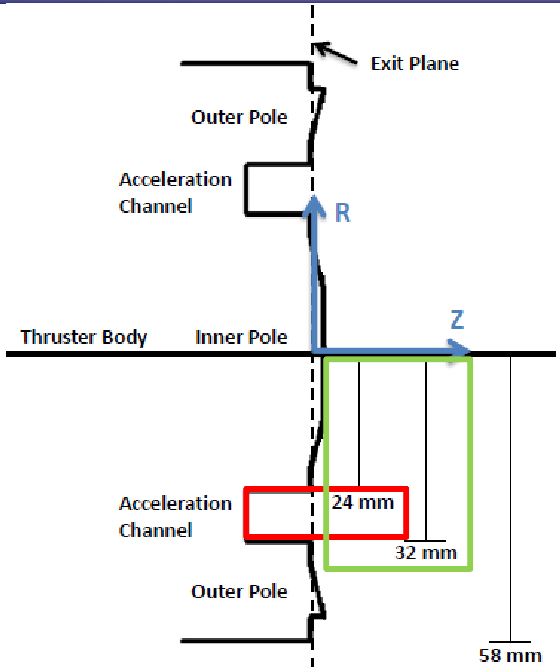
6. Repeat for t_1, t_2, etc.

↓

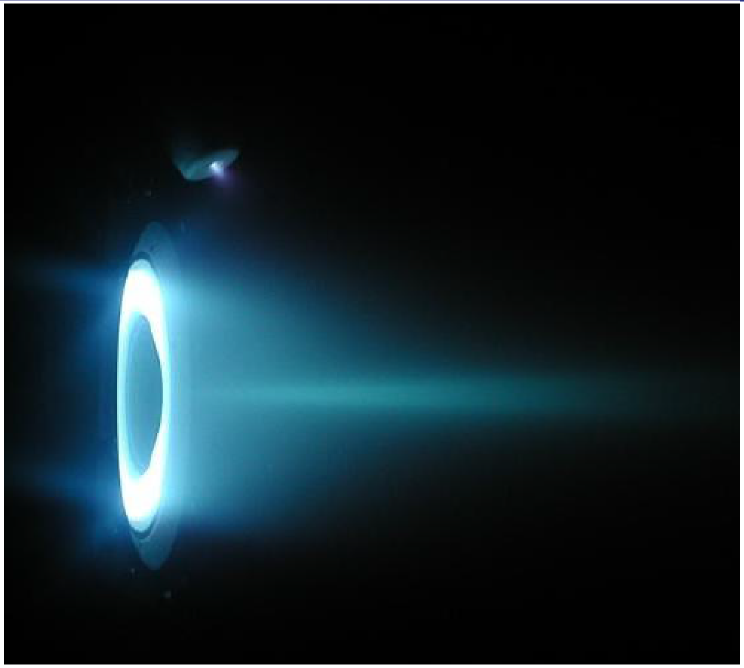
Lineshapes for t_0, t_1, t_2



BHT-600 Specifications



a) Schematic of BHT-600



b) BHT-600 Operating on Xenon

- **BHT-600**
  - **600 W annular Hall thruster**
  - **Manufactured by Busek Co.**
- **Tested in Chamber 6 at AFRL**
  - **Background pressure 1.2x10^{-5} Torr**

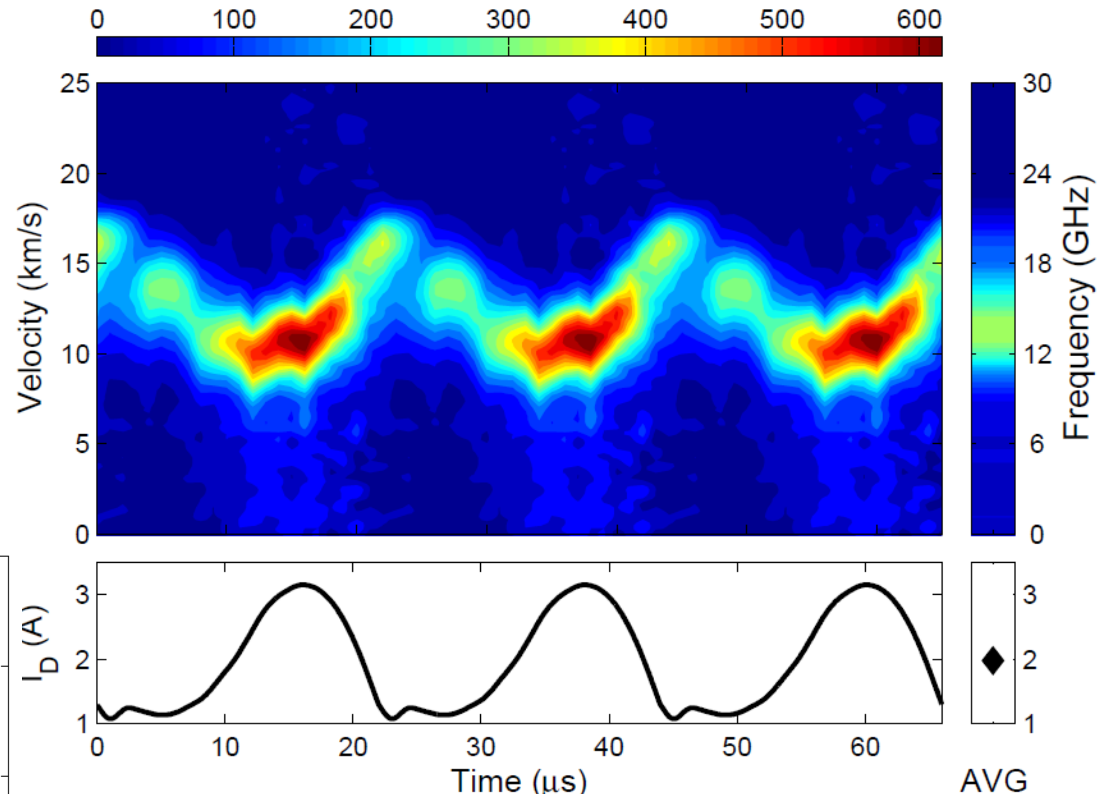
Nominal Operating Conditions

Anode Flow	2.45 mg/s Xe (20.5 sccm)
Cathode Flow	197 μg/s Xe (1.5 sccm)
Anode Potential	300 V
Anode Current	2.05 A
Magnet 1 Current	2.0 A
Magnet 2 Current	2.0 A

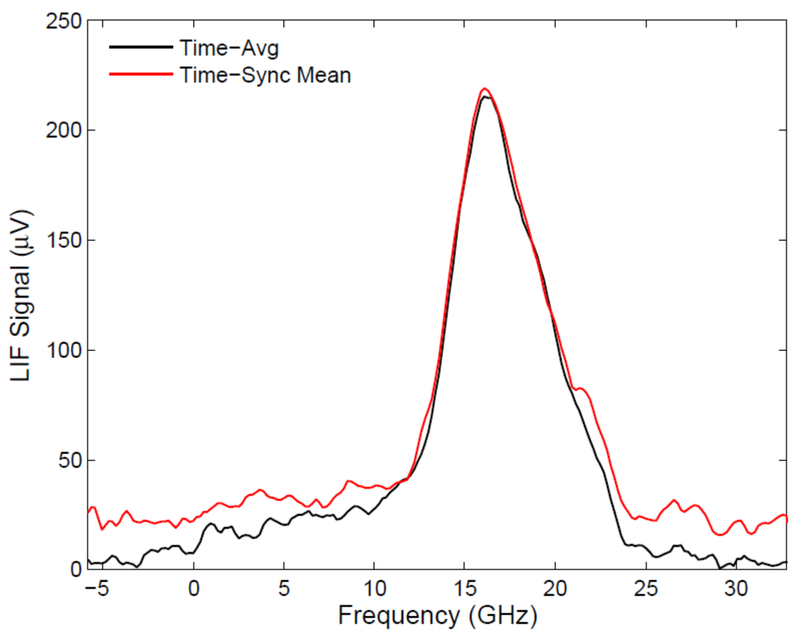
Velocity and Intensity Trends

- **Peak lineshape intensity**
  - **In phase with current**
  - **Intensity increases w/ growth of ion population**
- **Most probable ion velocity**
  - **90º phase lag relative to current**
  - **Max velocity after point of peak ionization**

➢ **Breathing mode cycle**



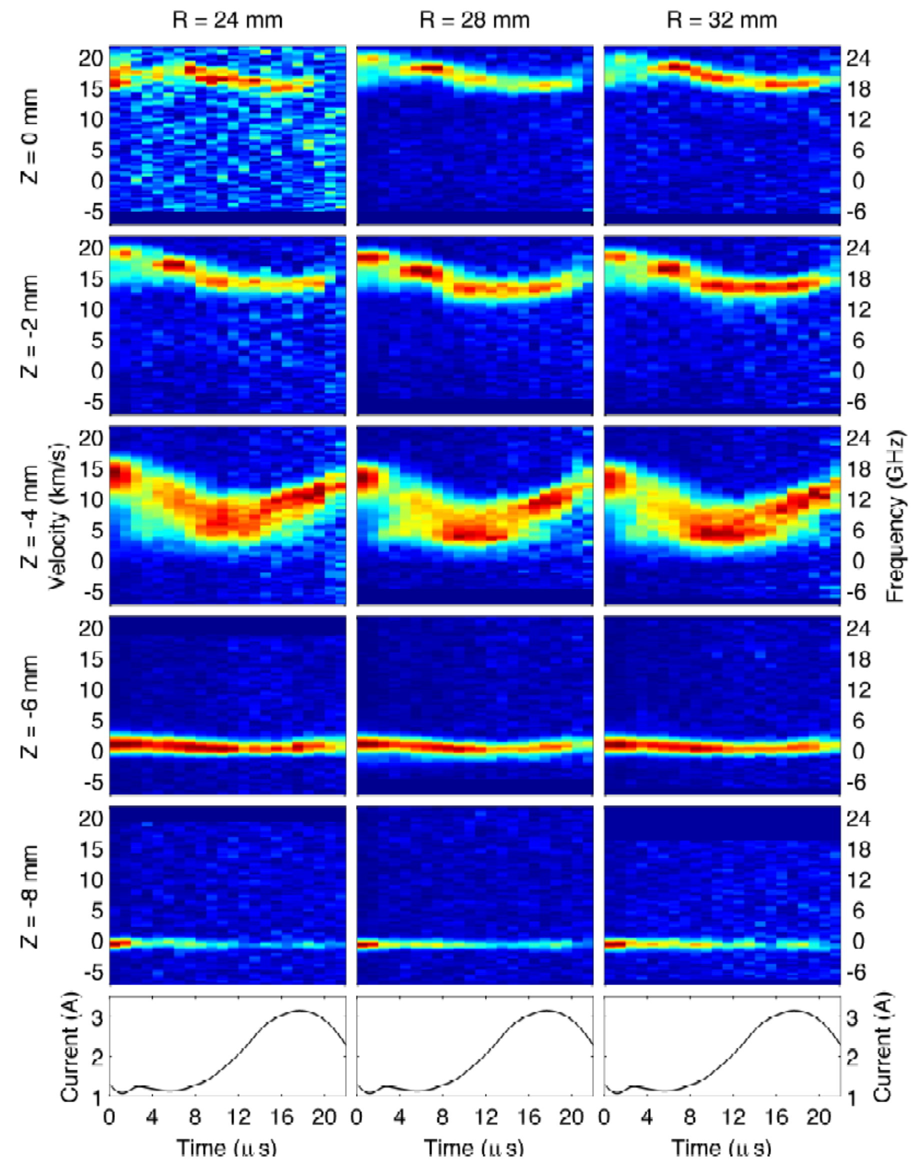
Most probable ion velocity and peak lineshape intensities for IVDFs measured along centerline of discharge channel (R = 28 mm, Z=-2 mm)



Average of individual time-synchronized velocity distribution function matches well with measured time-averaged velocity distribution

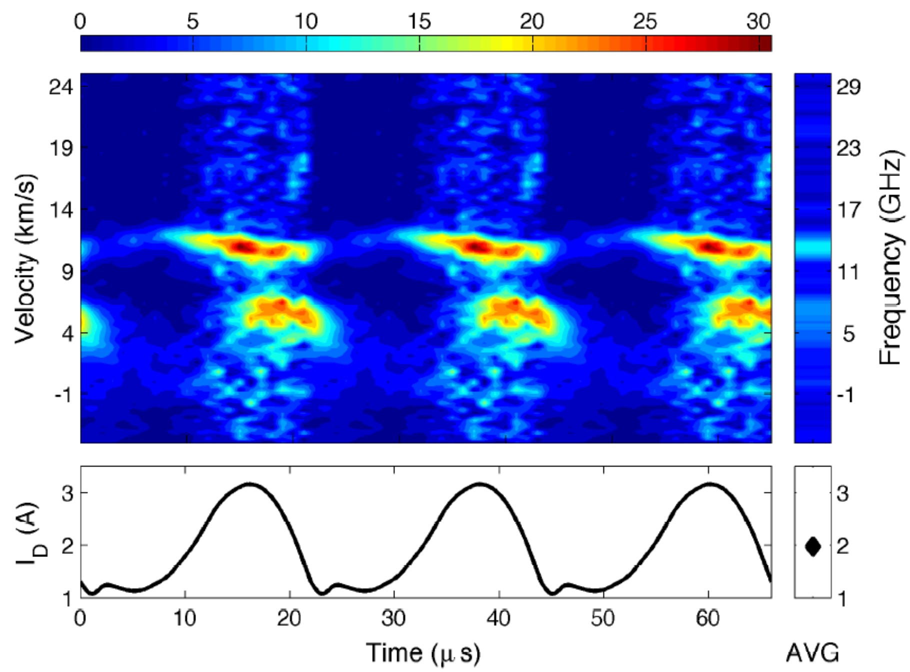
Channel IVDFs

- **Minimal radial variations in channel**
- **Z = -8 mm (near anode)**
  - **Slight negative velocity**
  - **Gradient-driven field reversal**
- **Z = -6 mm**
  - **Accelerating potential begins**
  - **Broader IVDFs**
- **Z = -4 mm**
  - **Significant broadening of IVDFs**
  - **Large temporal variations (5-13 km/s)**
  - **Spatial extent of propellant ionization and local potential drop fluctuate**
- **Z = -2 mm, Z = 0 mm**
  - **IVDFs narrow**
  - **More even acceleration in time**



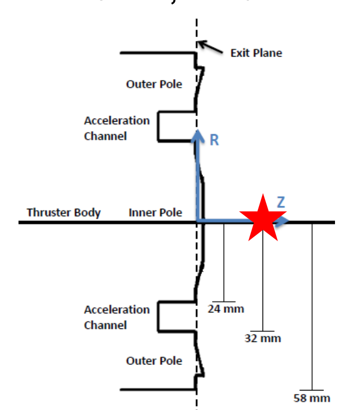
Near-Field Plume Measurements

- **Time-sync axial IVDFs obtained throughout near-field plume**
- **Secondary ion velocity population**
  - **Appears near centerline of thruster**
  - **Low velocity dominates at current minimum**
  - **Primarily caused by geometric effects**
  - **Other causes:**
    - **Charge exchange collisions w/ neutrals**
    - **Residual ionization downstream of main potential drop**



Axial ion velocity distributions vs. time at Z = 15 mm, R = 0 mm.

- **Upcoming radial IVDF measurements**
  - **Elucidate fluctuations in plume divergence**
  - **Ion velocity vectors compared to numerical models in HPHall, emission data**



Summary

- **Laser diagnostic techniques have been developed alongside propulsion technologies**
- **Allow us to better understand propulsion technologies that were previously 'black boxes'**
- **In-situ, time-resolved diagnostics are becoming more important for understanding spacecraft interactions, pushing towards predictive modeling & simulation efforts**

Thank You!

Dr. Bill Hargus – Air Force Research Laboratory

Chris Young, Dr. Andrea Lucca-Fabris,
Prof. Mark Cappelli – Stanford University

Amanda Makowiecki , Torrey Hayden,
Prof. Greg Rieker – U. of Colorado, Boulder